

Asteroseismology and the Solar-Stellar Connection

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Abstract. In March 2009, NASA will launch the Kepler satellite—a mission designed to discover habitable Earth-like planets around distant Sun-like stars. The method that Kepler will use to detect distant worlds will only reveal the size of the planet relative to the size of the host star, so part of the mission is devoted to characterizing other suns using asteroseismology. In this proceedings, I give a broad overview of the Kepler mission and the data that it will produce, with a special emphasis on how it could improve our understanding of solar and stellar dynamos. I conclude with an update on the development of a stellar modeling pipeline for interpreting asteroseismic observations.

1. Song of the Stars

In the region of Canada that is now Quebec and Ontario, a Native American tribe known as the Algonquin developed a detailed myth about the annual path of the Big Dipper around the north celestial pole, which they chanted in their “Song of the Stars”:

We are the stars which sing,
We sing with our light;
We are the birds of fire,
We fly over the sky.

If we think of asteroseismology as the study of “stars which sing with their light”, then NASA’s Kepler mission is poised to record the largest stellar choir ever assembled. In this proceedings, I will give a brief overview of the Kepler mission, followed by a review of the specific types of data the satellite is likely to produce which have the potential to improve our understanding of solar and stellar dynamos. I will conclude with an update on the work I have been doing to prepare for the massive wave of data soon expected from Kepler.

2. Overview of the Kepler Mission

If you visit NASA’s homepage for Kepler (<http://kepler.nasa.gov/>), the banner across the top of the page proclaims it to be “a search for habitable planets.” Indeed, the primary science goal of the Kepler mission is to find Earth-like planets with orbits inside the habitable zones of Sun-like stars. So why is asteroseismology a part of this mission at all? Well, Kepler aims to detect these habitable planets through high precision photometry of exoplanet transits. The small dip in the amount of light coming from the system is a measure of the

size of the planet *relative* to the size of the star. Thus, for a high precision determination of the *absolute* size of the planet, the stellar radius needs to be measured reliably. Asteroseismology using the solar-like oscillations observed in these stars should be able to measure the absolute stellar radii with a precision of 2-3% (Kjeldsen et al. 2008a), leading to a comparable precision on the radii of any planets that are eventually discovered.

The Kepler mission is currently scheduled for launch in March 2009, and will target a single large field of view (105 square degrees) just above the Galactic plane in the constellation Cygnus. The idea is to look close enough to the plane that it can monitor $\sim 10^5$ solar-type stars, which should be sufficient to discover dozens of Earth-like planets if they are at all common—but far enough out of the plane that it reduces the contamination from giants, which are less interesting from the standpoint of habitable planets. The satellite will stare at this one field for the entire nominal mission lifetime of 3.5 years—enough to detect three transits separated by 1 year in a reasonable sample of stars—but depending on the success of the program, it may optionally be extended for an additional 2 years. It will monitor the brightness of 100,000 stars with sub-rastered images processed on-board into 30-minute sums, while a revolving selection of 512 stars can be monitored with a 1-minute cadence to document solar-like oscillations. Initially, all of these short cadence targets will be specified by the Kepler Asteroseismic Science Consortium (KASC, <http://kepler.asteroseismology.org/>), which is being organized through the University of Aarhus in Denmark and is open to anyone who signs NASA's non-disclosure agreement regarding possible exoplanet signatures discovered in the data. As the mission continues, some fraction of the short cadence targets will be reserved to characterize the host stars of exoplanets after they are discovered. A new selection can be specified every 3 months, so by the end of the mission there should be asteroseismic data on many hundreds of solar-type stars monitored continuously from a few months up to several years.

3. New Data for Dynamo Modeling

In this section I outline the various types of data that are likely to emerge from the Kepler satellite, with a special emphasis on information that could improve our understanding of solar and stellar dynamos.

3.1. Surface Differential Rotation

Even without the short cadence data for asteroseismology, Kepler will yield high precision time-series photometry for many stars that will be sufficient to characterize the surface differential rotation through detailed spot modeling. Essentially, the photometry will be so precise that we will be able to see the signature of individual star-spots rotating into view—and the continuous monitoring will allow us to watch as spots at different stellar latitudes lap each other so we can derive their locations and rotation rates without ambiguity. A beautiful example of this technique comes from three seasons of photometry of the young solar-type star κ^1 Ceti from the MOST satellite (Walker et al. 2007). For each season of data, ranging from 15 to 30 days of observations, the MOST team fit the light curves with a stellar spot model. The rotation rates of the derived spots at various latitudes on the surface of the star exhibit the same

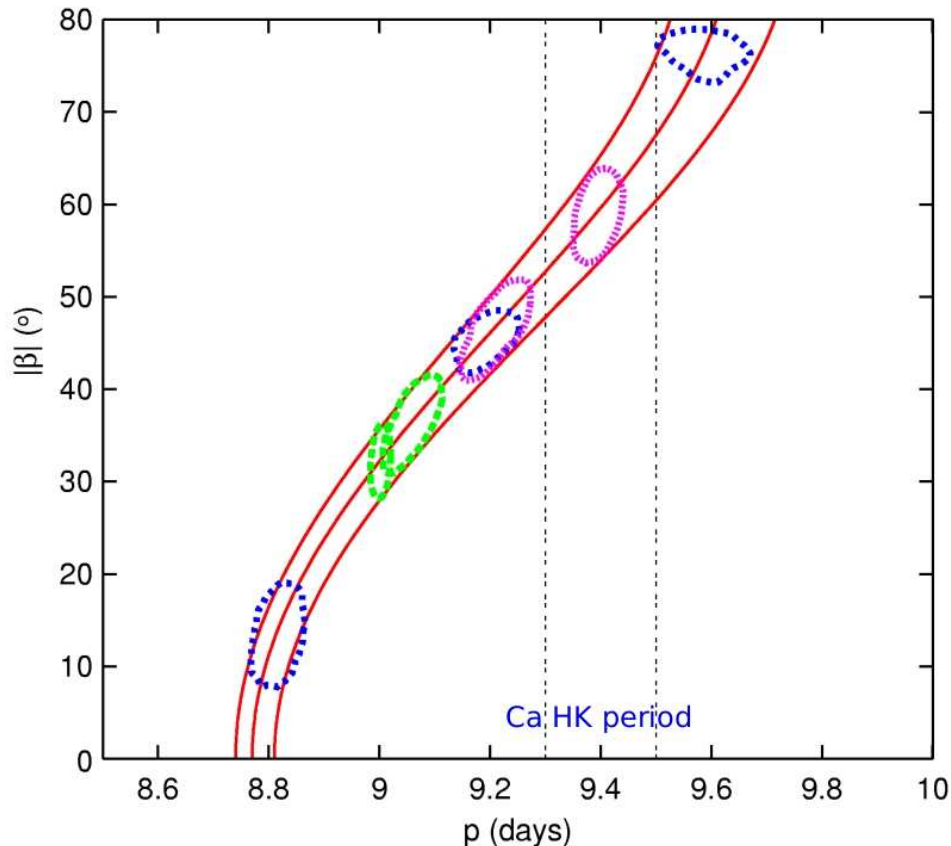


Figure 1. The latitudes and rotation rates of star-spots on κ^1 Ceti from three seasons of MOST observations, showing the same pattern of surface differential rotation as the Sun (adapted from Walker et al. 2007).

functional form as the Sun’s surface differential rotation, with spots near the equator moving around more quickly than spots closer to the pole (see Figure 1). The Kepler data will allow similar differential rotation measurements for up to 100,000 solar-type stars, and over the lifetime of the mission this may even allow the construction of rudimentary “butterfly diagrams” showing the migration of activity belts through at least a fraction of the magnetic cycle.

3.2. Stellar Density and Age

Among the stars that Kepler observes for asteroseismology, even those with the lowest signal-to-noise ratio—where individual oscillation frequencies may not be detected—should reveal the characteristic frequency spacings that probe the mean stellar density and age. Asteroseismic data of the Sun observed as a star, without spatial resolution across the disk, show a regular pattern of radial ($\ell = 0$) and quadrupole ($\ell = 2$) mode pairs interleaved with pairs of dipole ($\ell = 1$) and octupole ($\ell = 3$) modes (see Figure 2). The so-called large frequency separation—the spacing between consecutive radial overtones

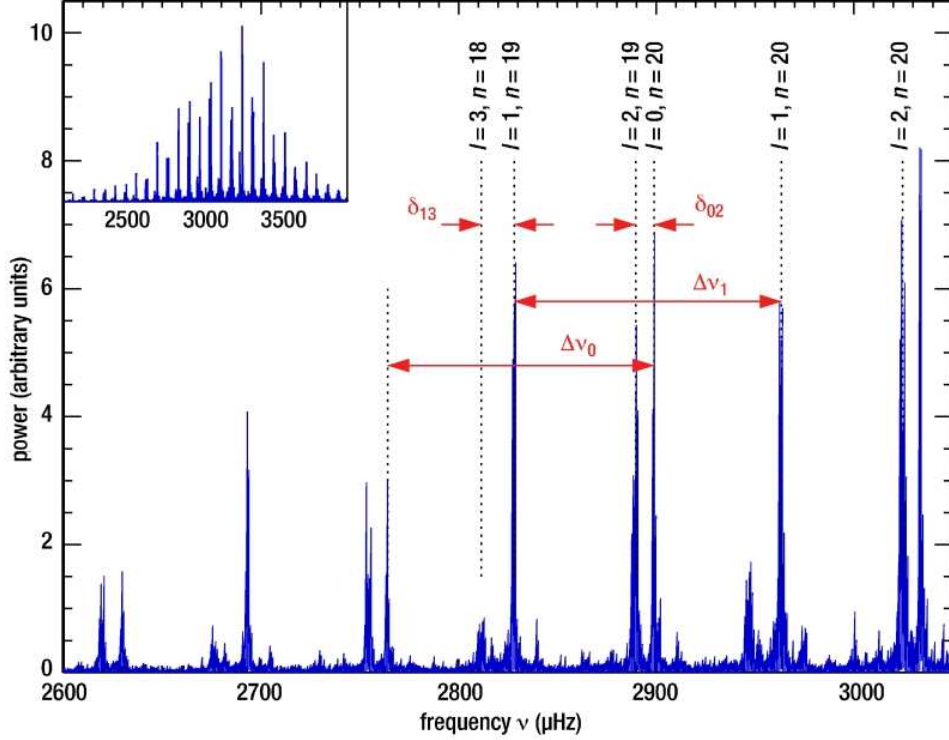


Figure 2. The pattern of oscillation frequencies seen in the Sun observed as a star, showing the characteristic large and small frequency spacings that indicate the mean density and age (adapted from Elsworth & Thompson 2004).

for modes with the same spherical degree—scales with the mean density of the star (Brown & Gilliland 1994). When combined with non-seismic observables such as the effective temperature and luminosity, the large separation can lead to reasonable estimates of the stellar mass and radius. A radial mode travels through the center of the star, while the nearby quadrupole mode with a lower radial overtone does not. This defines the so-called small frequency separation, which is sensitive to interior chemical gradients near the center of the star caused by nuclear processing of hydrogen into helium. This is a good proxy for the stellar age, and will allow Kepler to measure ages for these stars with a precision of about 10% of the main-sequence lifetime—compared to typical uncertainties of a factor of two for non-seismic age estimates. Together, these two characteristic spacings will significantly improve observational constraints on the evolution of magnetic activity and rotation across the entire region of the H-R diagram where solar-like oscillations are excited.

3.3. Radial Differential Rotation

For the brighter asteroseismic targets where the individual oscillation frequencies are detectable, the time series should be long enough to resolve rotational splitting of the modes into multiplets for stars with rotation rates between about 2 and 10 times the solar rate (Ballot et al. 2008). Slower rotation makes it diffi-

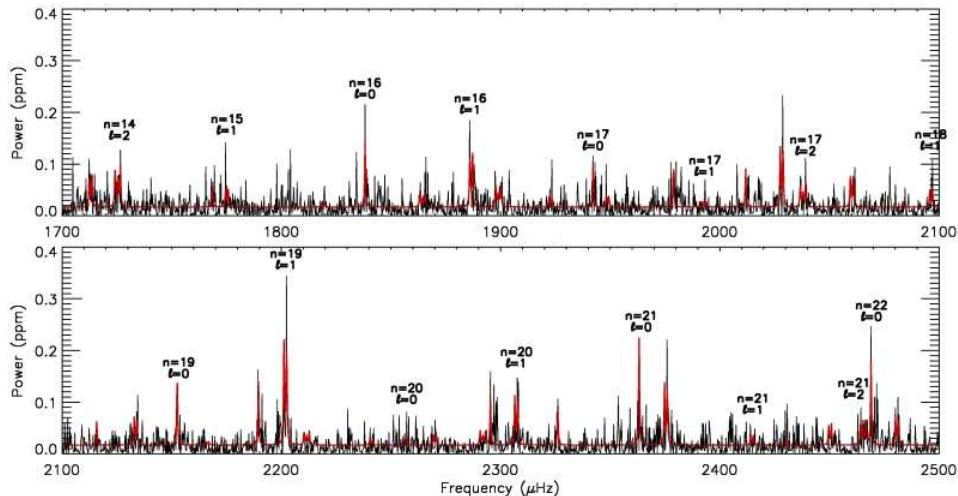


Figure 3. The rotational splitting as a function of radial overtone can provide indirect evidence of radial differential rotation since the modes sample slightly different regions of the star (adapted from Fletcher et al. 2006).

cult to resolve the individual components of each multiplet from their strongly overlapping Lorentzian profiles, while faster rotation produces a splitting that is comparable to the small separation—creating some ambiguity in the mode identification. A 50-day photometric time series of α Cen A from the WIRE satellite successfully resolved the rotational splitting in this star (see Figure 3; Fletcher et al. 2006). Measurements of the rotational splitting as a function of radial overtone can indirectly probe radial differential rotation, since the various modes sample slightly different (but overlapping) regions of the star. More directly, even with the limited set of low-degree oscillation frequencies that are available for distant stars, it is possible to construct inversion kernels that might detect a rapidly rotating core (Gough & Kosovichev 1993), although more recent work suggests that a significant detection may require unrealistically strong differential rotation (Chaplin et al. 1999).

3.4. Convection Zone Depth

For the very best and brightest asteroseismic targets, it may be possible for Kepler to obtain a frequency precision sufficient to measure the depth of the surface convection zone. This concept was recently demonstrated with simulated data for a 5-month observation of the star HD 49933 using the CoRoT satellite (Baglin et al. 2006). The second differences measure deviations from uniform spacing of a sequence of modes with the same degree. Sharp features inside the acoustic cavity, such as the base of the surface convection zone or the helium ionization region, create oscillatory signals in the second differences. Through detailed modeling, it is possible to derive the acoustic radii of these sharp features (see Figure 4). Although results have recently been published for a short CoRoT run on HD 49933 (Appourchaux et al. 2008) and a 5-month run on the same field has now been completed, it is not yet known whether the simulated data were a reasonable approximation of the actual observations. The Kepler mission

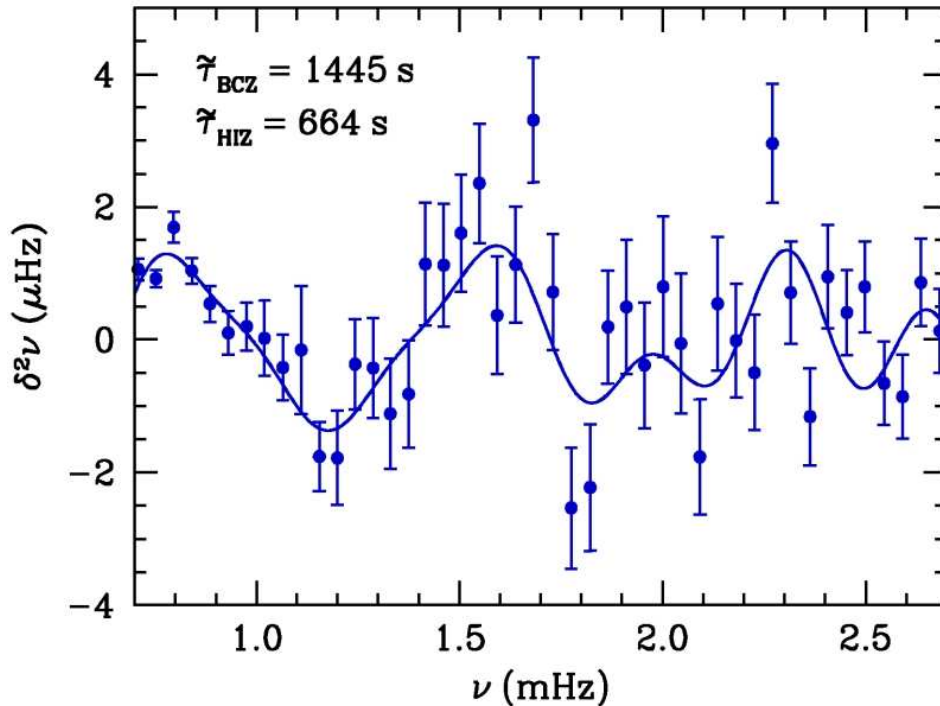


Figure 4. The base of the surface convection zone creates an oscillatory signal in the second differences that can indicate the acoustic radius of this sharp feature from detailed modeling (adapted from Baglin et al. 2006).

has the potential to measure convection zone depths by applying this technique to dozens and possibly hundreds of solar-type stars.

3.5. Cycle-induced Frequency Shifts

The influence of the solar cycle on the Sun’s p-mode frequencies was first detected nearly two decades ago (Libbrecht & Woodard 1990), and was shown to depend on both the frequency and the spherical degree of the mode. Even the lowest degree p-mode frequencies from Sun-as-a-star observations show a strong correlation with the solar cycle (Salabert et al. 2004), so there is good reason to believe that we will see similar frequency shifts in other stars. In principle, these shifts might provide unique constraints on the underlying physical mechanism. Recently, Metcalfe et al. (2007) developed a parameterization of the source of these frequency shifts in the Sun, and demonstrated that it could account for most of the dependence on both frequency and spherical degree (see Figure 5). They applied this model to observations of the subgiant star β Hydri and, although the precision of the asteroseismic data was not sufficient for a quantitative test, they showed that the appropriately scaled model could qualitatively account for the frequency shifts observed in this star. The Kepler mission will document similar shifts in hundreds of solar-type stars, allowing us to move beyond a simple scaling from the solar case and gradually leading to a broader context for our understanding of the solar dynamo.

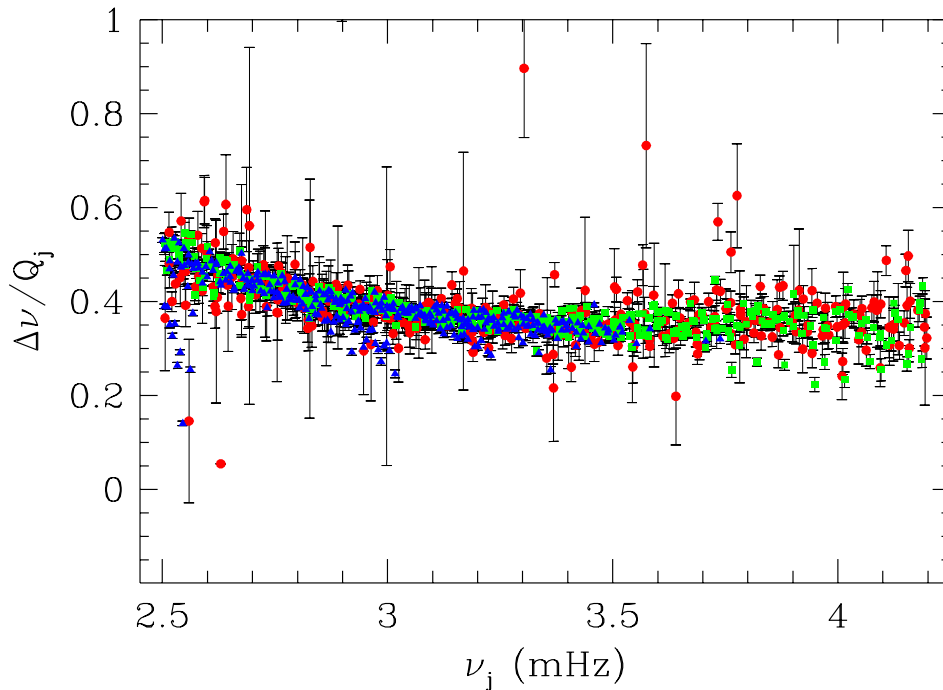


Figure 5. The solar cycle alters p-modes as a function of their frequency and spherical degree, but both dependencies largely disappear when normalized by an analytical model of the source (adapted from Metcalfe et al. 2007).

4. Stellar Modeling Pipeline

Over the past few years, I have been working with Jørgen Christensen-Dalsgaard to develop a general purpose tool for modeling asteroseismic data. The basic idea is that, given an observed set of solar-like oscillation frequencies and non-seismic constraints, this software pipeline will return the optimal set of model parameters. It uses a genetic algorithm to explore a broad swath of the H-R diagram (see Figure 6), probing masses between 0.75 and 1.75 M_{\odot} , initial metallicities between 0.002 and 0.05 sampled evenly in the log, initial helium mass fractions between 0.22 and 0.32, mixing-length parameters between 1 and 3, and evolutionary states from the zero age main sequence to the base of the red giant branch. By simultaneously matching all of the data, the method can find the optimal balance between asteroseismic and other constraints.

4.1. Application to BiSON Data

As a demonstration of the method, our first application has been to Sun-as-a-star observations from the BiSON network, using 36 oscillation modes with $\ell=0-2$ in a range of frequencies near 3 mHz and the solar luminosity and effective temperature with errors scaled up to what we expect from the Kepler mission. The genetic algorithm successfully matched the observed frequencies to better than 0.6 μHz by including an empirical surface correction following Kjeldsen et al. (2008b), while simultaneously matching the temperature and age to $\pm 0.1\%$ and

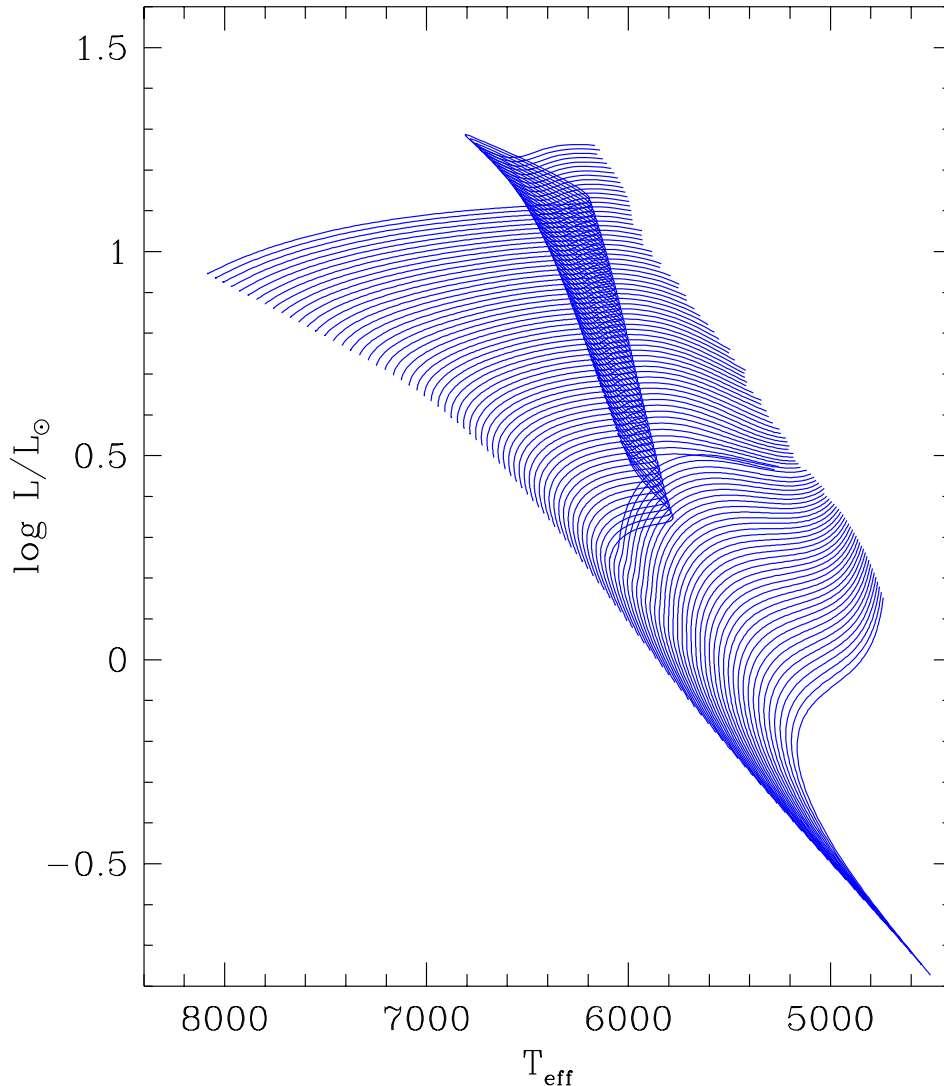


Figure 6. Our stellar modeling pipeline explores a broad swath of the H-R diagram to find the globally optimal model for any set of asteroseismic data from solar-like oscillations, along with any other observational constraints.

the luminosity and radius within $\pm 0.4\%$. Although the fit used a limited range of frequencies and did not include $\ell=3$ modes, the optimal model also matched the modes with lower frequencies and higher degree (see Figure 7) and recovered the known solar properties within reasonable tolerances.

4.2. TeraGrid Portal

Although the genetic algorithm requires far fewer model evaluations to find the global solution relative to a complete grid at the same sampling density, it is still quite computationally intensive—running on 512 processors for about a

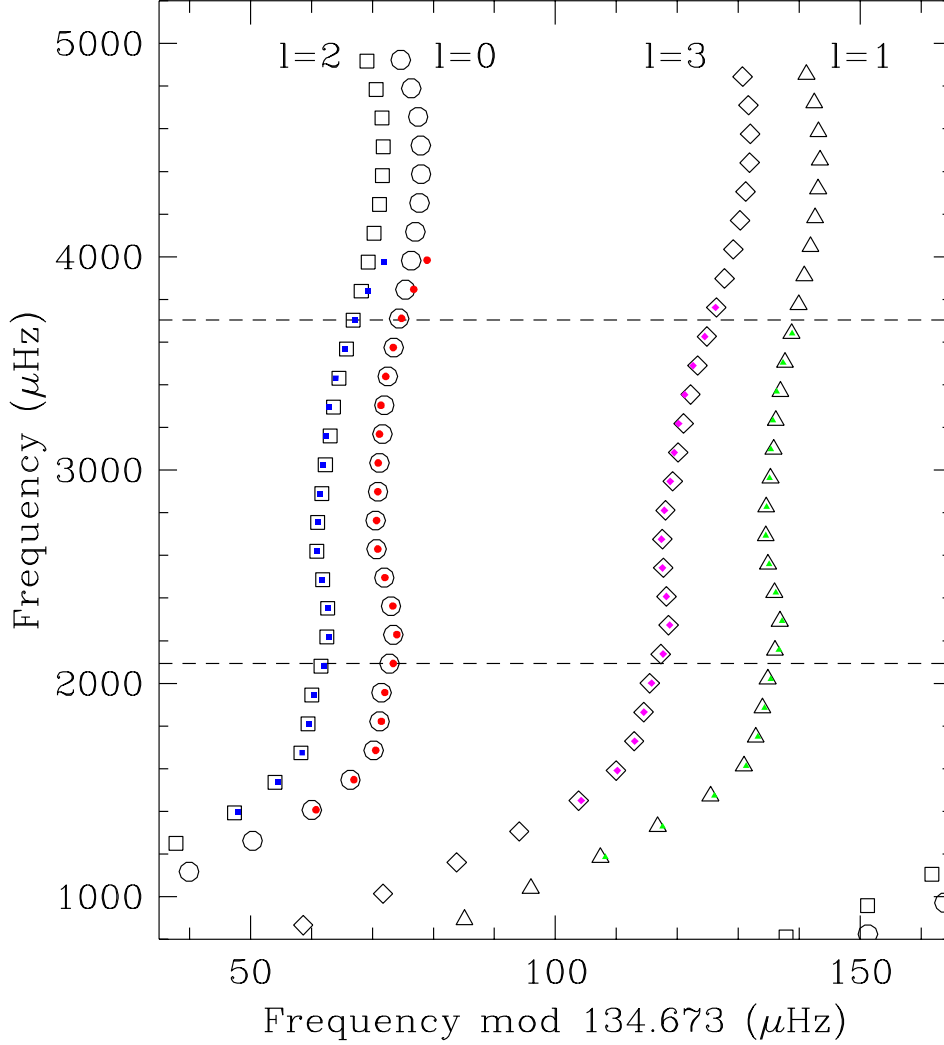


Figure 7. An echelle diagram for the BiSON data (solid points) along with the optimal model from our asteroseismic modeling pipeline (open points), which only used the $\ell=0-2$ frequencies between the dashed lines for the fit.

week. To encourage a uniform analysis of the asteroseismic data from Kepler, we plan to make our pipeline available as a web-based tool tied to computational resources on the TeraGrid. This may help minimize any systematic errors that could arise if the data were analyzed by many people using different codes and optimization schemes. Through the web interface, users will be able to upload or enter their observational data, click a button, and a week later they will be emailed a file with all of the details of the optimal model. Since it requires about 100,000 model evaluations to find the best model for each star, we plan to build an archive that can be used for quick searches based on the accumulated incomplete grid. Over time, as we analyze many stars, this partial grid will grow more and more useful to identify reasonable models—particularly for new

data sets that resemble earlier ones. Another service will simply be a user-friendly interface for the modeling code, allowing users to specify a single set of parameters and run one instance of the model, which will then be archived on the website. Of course, for users with access to large clusters or supercomputers, we will also provide the source code and documentation.

5. Summary

The Kepler mission promises to revolutionize the quality and quantity of asteroseismic data available for solar-type stars, and it will significantly contribute to research topics related to the solar-stellar connection. The mission needs asteroseismology to determine the absolute sizes of any potentially habitable Earth-like planets that might be discovered. It will also yield a wide variety of data that will be useful for calibrating dynamo models, sampling many different sets of physical conditions and evolutionary phases to complement the well-studied solar example. A uniform analysis of the asteroseismic data will help minimize systematic errors between the parameter values obtained for different stars, and such an analysis will be facilitated by our TeraGrid-based community modeling tool. The “stars which sing with their light” have many secrets to tell us, and the Kepler satellite will allow us to listen as never before.

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